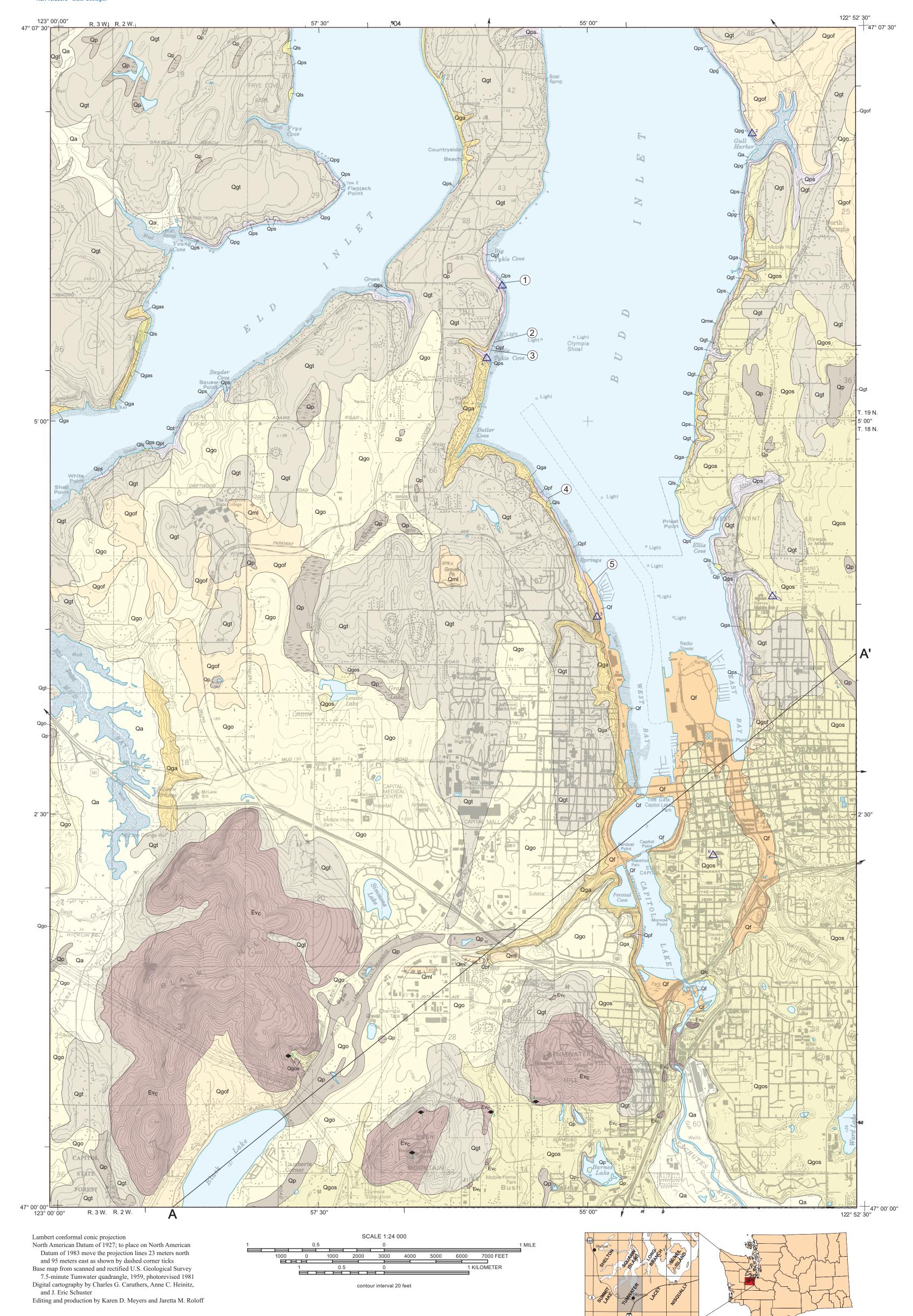


undifferentiated Pleistocene deposits

vertical exaggeration 5x



Geologic Map of the Tumwater 7.5-minute Quadrangle,

Thurston County, Washington

by Timothy J. Walsh, Robert L. Logan, Henry W. Schasse, and Michael Polenz

EXPLANATION ———— – – – Contact—dashed where inferred, queried where uncertain ——— — — — — — Thin glacial till (unit Qgt)—dashed where inferred ? Dip-slip fault—direction of movement shown by arrows queried where uncertain

undifferentiated Pleistocene deposits

undifferentiated bedrock

### **INTRODUCTION**

The Tumwater quadrangle is located at the south end of Puget Sound and includes the cities of Tumwater and Olympia. The quadrangle is mostly urban and residential land.

## **GEOLOGIC HISTORY**

Late Wisconsinan–age Vashon Drift covers most of the quadrangle. Pre-Vashon units are generally exposed only along coastal bluffs or stream banks, where mass wasting is common. Landslides and colluvium disrupt and obscure the continuity of exposures so that pre-Vashon geologic history is not easily deciphered. In the Puget Lowland south of Tacoma, all finite radiocarbon ages reported before 1966 are suspect due to laboratory contamination (Fairhall and others, 1966, p. 501). Stratigraphic assignments based on these radiocarbon ages are now questionable and need to be re-evaluated. We have systematically sampled all datable material from nonglacial sediments subjacent to the Vashon Drift and found them to be older than previously reported. With a few exceptions, these sediments have been beyond the range of radiocarbon dating.

The antiquity of the pre-Vashon units causes radiocarbon dating to be of little help for making correlations, and abrupt facies changes within glacial and nonglacial units also render correlations tenuous. Despite these difficulties, we have developed a conceptual model for the more recent pre-Vashon geologic history that is consistent with our observations but by no means compelling. The oxygen-isotope stage 6 glaciation, called the Double Bluff Glaciation in northern Puget Sound, was probably as extensive as the stage 2 or Vashon Stade of the Fraser Glaciation (Mix, 1987; Fig. 1). The end moraines of this glaciation lie a short distance beyond the inferred limit of the Vashon ice in the vicinity of Tenino, south of this quadrangle (Lea, 1984). Subglacial erosion was probably similar to the erosion that Booth (1994) documented beneath Vashon ice and would have left accommodation space for deposition during the interglacial time of oxygen-isotope stage 5. The oxygen-isotope stage 4 glaciation, called the Possession Glaciation in northern Puget Sound, was mild relative to stages 2 and 6 (Mix, 1987; Fig. 1), represented by the Vashon and Double Bluff Drifts respectively in the Puget Lowland. The Possession ice sheet probably did not extend far south of Seattle (Lea, 1984; Troost, 1999). Because the ice sheet blocked drainage out of Puget Sound to the Strait of Juan de Fuca, a proglacial lake was impounded covering most of the southern Puget Lowland. Streams flowing into this lake, such as the Nisqually, Puyallup, and Skokomish Rivers, formed an alluvial plain and deltas grading to lake level. These nonglacial sediments, deposited during stage 4, are all radiocarbon-infinite and overlie and interfinger with Possession glacial outwash deposits. Once Possession ice no longer impounded the lake (but sea level was still significantly below modern sea level), existing drainages deeply and rapidly incised into their former alluvial plains and became entrenched. At least initially, stage 3, called the Olympia nonglacial interval locally (Armstrong and others, 1965), was characterized by downcutting and erosion. As sea level began to rise, most deposition was confined to these entrenched channels. Because stage 3 sea level was probably about 100 ft lower than modern sea level (Ludwig and others, 1996, and references therein), stage 3 deposits were areally restricted. As Vashon ice advanced and sea level fell again at the beginning of stage 2, these rivers preferentially downcut in the same channels, thereby eroding are rare above sea level. For pre-Vashon nonglacial deposits that are radiocarbon-infinite, it is difficult to distinguish deposits of stage 3 from deposits of stages 4 and 5, and we have not attempted to do so in the present mapping. In some outcrops, however, tephras are present that provide a tool for geochemical correlation to known eruptions on nearby Cascade stratovolcanoes. Tephra correlations appear promising but will require more data.

As Vashon ice moved southward and grounded across the Strait of Juan de Fuca during stage 2, it dammed the northern outlet of the Puget Sound basin. Proglacial streams carried fluvial sediments southward into the Puget Lowland, filling proglacial lakes and eventually the Puget Sound basin first with silts, then sands and gravels. These sediments form the 'great lowland fill' of Booth (1994). Ice overrode these sediments, covering most of them with till, or scoured them away to deposit till directly onto pre-Vashon sediments or bedrock. Subglacial channels were subsequently eroded into the fill. Proglacial lakes became impounded in these channels at different elevations above today's sea level as ice impinged on divides. The former lakebeds are presently the southernmost inlets of Puget Sound. (For a more thorough discussion of the subglacial channel network, see Booth, 1994, and Booth and Goldstein, 1994.) As these proglacial lakes spilled into lower-elevation basins and channels near the end of the Pleistocene, they deposited coarse, steeply dipping deltaic gravels along the margins of the channels and basins. Some of these deposits can be found near Shelton (to the west of this quadrangle) and near Steilacoom and Fort

Much of the drainage originating from the ice sheet flowed

southward and southwestward toward the Chehalis River. Some of the drainage probably occurred as glacial-lake outburst floods when valleyblocking ice dams were breached during ice retreat. Deep troughs were carved out of the fill by subglacial fluvial erosion, and extensive and complex terraces and braided channels were formed. As the ice receded and uncovered the troughs of Eld and Budd Inlets, streams near Olympia filled the deep troughs with sandy sediments characterized by northward-directed paleocurrent indicators. These sediments provide evidence that drainage reorganized to flow northward through the recently formed outwash plain. The thickness of these sediments (unit Qgos) varies substantially throughout the area, reaching more than 400 ft in a geotechnical borehole at the Port of Olympia (Washington Public Power Supply System, 1974). Unit Qgos is important because it is widespread throughout the populous South Sound area and appears to behave differently from the rest of the Vashon Drift during earthquakes (Palmer and others, 1999a,b; Bodle, 1992; King and others, 1990). In the waning stages of the Fraser Glaciation, glacial Lake Russell covered a large area of the southern Puget Lowland and deposited a relatively thin layer (1–10 ft) of fine-grained varved sediments (unit Qgof) to an elevation of about 140 ft. These lacustrine silts (and rare clays and peats) commonly overlie and interfinger with the informally

### named Tumwater sand (unit Qgos) and Vashon till (unit Qgt). PREVIOUS GEOLOGIC MAPPING

The glacial history and geology of south Puget Sound are summarized by Bretz (1913), who mapped the entire Puget Sound basin in reconnaissance. Noble and Wallace (1966) mapped all of Thurston County for a small-scale water resources study. The Coastal Zone Atlas (Washington Department of Ecology, 1980) provides mapping of a 2000 ft wide strip along the shoreline at a scale of 1:24,000. Walsh (1987), Walsh and others (1987), and Palmer and others (1999a) compiled and augmented previous mapping.

# **MAPPING METHODS**

Lewis (to the east).

For the present map, we inspected available construction site excavations, gravel pits, and roadcuts. We surveyed the shorelines by boat and took samples and measured sections at cliff exposures. Contacts between map units are commonly not exposed and are only approximately located on this map. They are generally located by outcrop mapping, air photo and Light Detection and Ranging (LIDAR) interpretation (Fig. 2), and interpretations of water well logs from Washington Department of Ecology. Geotechnical boreholes provided data on the thickness of unit Qgos (herein informally named the Tumwater sand, a facies of the recessional outwash of the Vashon Drift) near the Port of Olympia. U.S. Department of Agriculture soil maps (Pringle, 1990) helped guide the location of peats and the contacts between sandy and gravelly units. Location accuracy of contacts is judged to be about 200 ft in general. In addition, the contacts between some units are gradational. We have tried to consider geotechnical significance in mapping geologic units and have attempted to show units only where they are thicker than 5 to 10 ft or mask the underlying

◆3 Geochemistry sample location  $\triangle^2$  Radiocarbon sample location

# **Quaternary Unconsolidated Deposits**

surface morphology; includes engineered and nonengineered fills; shown only where fill placement is significance, and readily verifiable.

Modified land-Soil, sediment, or other geologic material that has been locally reworked to modify the topography by excavation and (or) redistribution; includes mappable sand

deposited by mass wasting; depending on degree of activity, location within the slide mass, type of slide, cohesiveness, and competence of materials, may be unstratified, broken, chaotic, and poorly sorted or may retain primary bedding structure; may be cut by clastic dikes or normal or reverse shear planes; surface is commonly hummocky in lower reaches of deep-seated landslides or 'stepped' with forwardor back-tilted blocks in headward areas; deep-seated slides tend to be relatively large. Slow-moving slumps (Varnes, 1978) commonly transform into slump–earth flows, can commonly be recognized by bowed or randomly tilted trees, and most commonly occur at the interface between poorly compacted, poorly cohesive, permeable sands and underlying, relatively impermeable silt or clay layers; shallow, more rapid debris flows commonly occur at the interface between impermeable substrate, such as till, and shallow, loose, permeable soils that are rich in organic matter. Rock topples and (or) falls that are too small to be shown at the map scale occur wherever near-vertical bluffs are present, typically because silt- or clay-rich layers such as units Qgof or Qps fail along bluffs. Unit Qls is shown only where landslides are large or obscure the underlying geology. Landslides generally are recognized by geomorphology but may be historically active and damaging, such as the landslide mapped at Sunrise Beach (Shannon & Wilson, 1999) and the landslides triggered by immediately south of Interstate Highway 5 and on the southwest shore of Capitol Lake.

Age of maximum Vashon ice advance in the map area was previously estimated to be approximately 14,000 radiocarbon yr B.P. based on apparent post-glacial deposits in the central Puget Lowland that were radiocarbon dated at about 13,600 radiocarbon yr B.P. (Porter and Swanson, 1998). However, five more-recently obtained radiocarbon dates from deposits that directly underlie Vashon till in the southern Puget Lowland, including a glaciolacustrine deposit in the Nisqually quadrangle (Walsh and others, 2003a), indicate a maximum ice advance after about 13,400 radiocarbon yr B.P. (Borden and Troost, 2001), which leaves only about 200 years for the glacial advance into and recession from the southern Puget Lowland. Most exposures mapped as Vashon till lack geochronologic data and are identified based on occurrence at or near the top of the stratigraphic section.

Latest Vashon fine-grained sediments—Lacustrine clayey and (or) fine sandy silt with sparse, disseminated dropstones; laminated and commonly vertically jointed; medium gray where fresh to pale yellow where dry and oxidized; distinguished by relatively darker (chocolate brown in oxidized exposures) horizontal bands about 1 in. thick that may represent annual winter depositional layers in a varve sequence; no more than about 20 apparent varves were counted in any exposure, suggesting a short life for the glacial lake(s) in which unit Qgof was deposited; present in deposits up to 10 ft thick over much of southern Puget Lowland and most commonly found at elevations below about 140 ft; mapped where it is thought to be at least about 5 ft thick or where it masks the underlying geomorphology; includes deposits of glacial Lake Russell and other lakes of the Vashon glacial recession.

Latest Vashon recessional sand and minor

silt—Moderately well-sorted, moderately to well-rounded, fine- to medium-grained sand with minor silt; noncohesive and highly permeable; thickness inferred from wells reaches up to 420 ft (Washington Public Power Supply System, 1974; Fig. 3); deposited in stream channels, inset terraces, and deltas flowing into or out of glacial lakes, predominantly glacial Lake Russell and successor lakes (Thorson, 1981); surrounds numerous steep-walled lakes and depressions (kettles), evidence that this unit was largely deposited during deglaciation when there was stagnant ice occupying much of the southern Puget Lowland; paleocurrents in the Deschutes basin inferred from cross beds are north-directed (Fig. 4); herein informally named the Tumwater sand, a facies of the recessional outwash of the Vashon Drift, for exposures along both the left and right banks of the Deschutes River between Tumwater Falls and Henderson Boulevard; the greatest thickness occurs where the sand was deposited by early Deschutes River reworking recessional outwash (unit Qgo) into glacial Lake Russell and later, glacial Lake Leland; grades into unit Qgof. Along the northwest shore of Black Lake in the southwest corner of the quadrangle, this unit is complexly interbedded with and overlain by unit Qgof, but water well data indicate that much of the polygon mapped as

unit Qgof is underlain by sand at very shallow depths. Vashon recessional outwash—Recessional and proglacial stratified, moderately to well-rounded, poorly to moderately sorted outwash sand and gravel of northern or mixed northern and Cascade source, locally containing silt and clay; also contains lacustrine deposits and ice-contact stratified drift. Some areas mapped as unit Qgo may instead be advance outwash (unit Qga) because it is difficult to tell the difference between the two without the presence of an intervening till.

## **DESCRIPTION OF MAP UNITS**

## HOLOCENE NONGLACIAL DEPOSITS

**Fill**—Clay, silt, sand, gravel, organic matter, shells, rip-rap, and debris emplaced to elevate the land surface and reshape relatively extensive, sufficiently thick to be of geotechnical

and gravel pits generally excavated into unit Qga. **Alluvium**—Silt, sand, gravel, and peat deposited in stream

Peat—Organic and organic-matter-rich mineral sediments deposited in closed depressions; includes peat, muck, silt, and clay in and adjacent to wetlands.

beds and estuaries; includes some lacustrine and beach

Mass wasting deposits—Colluvium consisting of loose soil and glacial sand and gravel deposited by soil creep and shallow ravelling on hillslopes, some of which occurred during the waning stages of the Vashon Stade of the Fraser Glaciation; shown where colluvium is of sufficient thickness to mask underlying geologic strata.

Landslide deposits—Rock, soil, and organic matter

# PLEISTOCENE GLACIAL DEPOSITS

## Deposits of Continental Glaciers—Cordilleran Ice Sheet Vashon Stade of the Fraser Glaciation

Glacial sediments described in this section consist mostly of rock types of northern provenance, most from the Canadian Coast Mountains. A wide variety of metamorphic and intrusive igneous rocks not indigenous to the Puget Lowland and generally southerly directed current indicators help distinguish these materials from the volcaniclithic-rich sediments of the eastern Puget Lowland and the Crescent Basalt– and Olympic core–rich sediments of the western Puget

Vashon till—Unsorted and highly compacted mixture of clay, silt, sand, and gravel deposited directly by glacier ice; gray where fresh and light yellowish brown where oxidized; very low permeability; most commonly matrix supported but may be clast supported; matrix generally feels more gritty than outwash sands when rubbed between fingers, due to being more angular than water-worked sediments; cobbles

### and boulders commonly faceted and (or) striated; ranges in thickness from wispy, discontinuous layers less than 1 in. thick to more than 30 ft thick; thicknesses of 2 to 10 ft are most common; may include outwash clay, sand, silt, and gravel, or ablation till that is too thin to substantially mask

the underlying, rolling till plain; erratic boulders are commonly associated with till plains but may also occur as lag deposits where the underlying deposits have been modified by meltwater; typically, weakly developed modern soil has formed on the cap of loose gravel, but the underlying till is unweathered; local textural features in the till include flow banding and apophyses that extend 10 to 15 ft downward into underlying sand and gravel (or till) and

Vashon advance outwash—Sand and gravel and lacustrine clay, silt, and sand of northern source, deposited during glacial advance; may contain some nonglacial sediments, such as cobbles and rip-ups of silt or peat as lag along channel sides and bottoms; gray where fresh, light yellowish gray where stained; sands (unit Qgas) locally 100 ft thick, well sorted, fine-grained with lenses of coarser sand and gravel; locally called Colvos Sand (Garling and others, 1965) and thought to be generally correlative to the Esperance Sand; generally permeable and porous with low cohesivity relative to overlying and underlying sediments,

are oriented transverse to ice-flow direction.

### PLEISTOCENE DEPOSITS OLDER THAN VASHON DRIFT

and subject to deep-seated landsliding.

Pre-Vashon glaciolacustrine deposits—Parallel-laminated clayey and (or) fine sandy silt with rare dropstones; medium gray where fresh to light tan where dry and oxidized to olive tan where moist and oxidized; very low permeability and porosity cause this unit to readily perch groundwater; softsediment deformation common; locally exceeds 100 ft in thickness; organic matter rare; interpreted to have been deposited in proglacial lakes even where dropstones have not been found, because interglacial conditions in south Puget Sound do not appear to be conducive to large lakes that lack significant amounts of organic matter; may include nonglacial lake deposits.

**Pre-Vashon sandy deposits**—Thin- to thick-bedded to cross-bedded sand interbedded with laminated silt and minor peat, diatomite, and gravel; commonly in upward-fining sequences; dominated by varied Cascade-source volcaniclithic rock types which give the sand a lavender color; generally of low permeability, causing a prominent spring line at an elevation of about 40 ft above mean sea level along the east shore of Budd Inlet from Olympia north to Priest Point; older than Vashon Drift and generally overlying or interbedded with unit Qpg; interpreted as nonglacial, but may include glacial-stage deposits, particularly from

oxygen-isotope stage 4 (Fig. 1). These sediments have previously been referred to the Kitsap Formation and were interpreted to have been deposited during the Olympia nonglacial interval (Garling and others, 1965; Noble and Wallace, 1966). Deeter (1979) however, has shown the type locality of the Kitsap Formation to include radiocarbon-infinite sediments of both glacial and nonglacial origin, and we follow his suggestion

that the name be abandoned. In the Squaxin Island quadrangle (see location map), a finite accelerator-mass-spectrometry radiocarbon date of  $33,220 \pm 300$  yr B.P. was obtained from a well near Boston Harbor from a sandy silt that is subjacent to Vashon Drift, and another sample from north of Sanderson Harbor yielded a  $38,060 \pm 620$  yr B.P. date (Logan and others, 2003a). Borden and Troost (2001) reported a radiocarbon age of  $41,380 \pm 1940$  yr. B.P. from Solo Point in the McNeil Island quadrangle, and Walsh and others (2003a) have reported finite radiocarbon ages in the Nisqually quadrangle. All ages we have obtained on this quadrangle, however, are radiocarbon-infinite (Table 1). All ages in unit Qps from the Longbranch, Lacey, and Shelton quadrangles are also

radiocarbon-infinite (Logan and others, 2003b,c; Schasse

and others, 2003). At the south end of Ketron Island in the McNeil Island quadrangle, a highly concentrated, sand-sized crystal-vitric pumice appears to have been deposited during oxygenisotope stage 7 (T. W. Sisson, U.S. Geological Survey, written commun., 2001; Logan and others, 2002; Fig. 1); this sand appears to be part of unit Qps, which continues around the east side of Ketron Island where it interfingers with unit Qpg. Another highly concentrated tephra is exposed near the southern tip of Anderson Island at Thompson Cove and the west shore of Nisqually Reach on the Lacey quadrangle (Logan and others, 2003c). Trace amounts of chemically similar pumice have also been found in sands exposed along Totten Inlet in the Shelton quadrangle. The age of this tephra is uncertain but may be as old as 100 to 200 ka (A. M. Sarna-Wojcicki, U. S. Geological Survey, written commun.,

Sediments mapped as unit Qps apparently were deposited during oxygen-isotope stages 3, 5, and 7 (Walsh and others, 2003b; Fig. 1), that is, during the Olympia interstade and much older nonglacial intervals. Because we can establish that not all pre-Vashon nonglacial sediments are correlative, we have chosen not to assign them a stratigraphic name.

Pre-Vashon gravel—Gravel and sand of northern provenance; stratigraphically underlies Vashon Drift; most commonly exposed beneath unit Qps; gravelly portions are relatively resistant to erosion; commonly tinted orange with iron-oxide staining; moderately to poorly sorted; commonly cross bedded but may lack primary sedimentary structures; inferred to be of glacial origin because interglacial conditions do not appear conducive to streams with sufficient competency to deposit widespread gravels in most of the Puget Lowland, and because the majority of the exposures include northern-source clasts.

**Pre-Vashon till**—Gray, unsorted, unstratified, highly compacted mixture of clay, silt, sand, and gravel of northern source; clasts have no weathering rinds; occurs about midway between White Point and Squaw Point on the southeast shore of Eld Inlet, where it is overlain with apparent conformity by pre-Vashon silt; other exposures of possible pre-Vashon till occur at mid-slope on Dickenson Point and at Sandy Point on Anderson Island, both northeast of this quadrangle, and in Hammersley Inlet near Shelton to the north-northwest of this quadrangle.

# **Tertiary Volcanic Rock**

Crescent Formation basalt (lower to middle Eocene)— Submarine(?) plagioclase-pyroxene tholeiitic (Table 2) basalt with local diabase and gabbro; pervasive zeolite and chlorite or chloritoid alteration in the matrix; commonly amygdaloidal with zeolite and (or) chlorite amygdules; dark gray with greenish tint, brown where weathered, reddish and variegated along altered contact zones; contains columnarjointed flows or sills, as well as breccias; refilled lava tubes common in breccias; orientation of columnar joints is commonly highly variable; highly vesiculated units are commonly highly altered and contain abundant clay minerals, whereas thick units with strong columnar joint formation tend to be less altered; commonly sheared and faulted; pillows, which are characteristic of the lower part of the Crescent Formation (Glassley, 1974; Tabor and Cady, 1978), are not observed in this quadrangle, suggesting that these rocks may be from the upper Crescent Formation; on the Olympic Peninsula, contains rare interbeds of laminar basaltic siltstone or fine sandstone with foraminiferal faunas referable to the Ulatisian Stage (Rau, 1981), although no fossils have been found in the Tumwater quadrangle.

## **ACKNOWLEDGMENTS**

We have benefited greatly from discussions with Derek Booth and Kathy Troost (Univ. of Wash.) and Ray Wells and Brian Sherrod (U.S. Geological Survey). This map is supported by the National Geologic Mapping Program under Cooperative Agreement No. 01HQAG0105 with the U.S. Geological Survey. New radiocarbon ages (Table 1) were provided by Beta Analytic, Inc. X-ray fluorescence analyses of basalt samples (Table 2) were provided by the Washington State University GeoAnalytical Lab.

### **REFERENCES CITED**

Armstrong, J. E.; Crandell, D. R.; Easterbrook, D. J.; Noble, J. B., 1965, Late Pleistocene stratigraphy and chronology in southwestern British Columbia and northwestern Washington: Geological Society

of America Bulletin, v. 76, no. 3, p. 321-330. Bodle, T. R., 1992, Microzoning the likelihood of strong spectral amplification of earthquake motions using MMI surveys and

no. 8, p. 695-698. Booth, D. B.; Goldstein, B. S., 1994, Patterns and processes of Raymond; Cheney, E. S., convenors, Regional geology of

Booth, D. B., 1994, Glaciofluvial infilling and scour of the Puget

south-central Puget Lowland, Pierce County, Washington:

Investigations 33, 33 p. Bretz, J H., 1913, Glaciation of the Puget Sound region: Washington Geological Survey Bulletin 8, 244 p., 3 plates. Deeter, J. D., 1979, Quaternary geology and stratigraphy of Kitsap

and quality of ground water in northern Thurston County, Washington: U.S. Geological Survey Water-Resources Investigations Report 92-4109 (revised), 230 p., 6 plates. Fairhall, A. W.; Schell, W. R.; Young, J. A., 1966, Radiocarbon dating at the University of Washington, III: Radiocarbon, v. 8, p. 498-506.

Drost, B. W.; Turney, G. L.; Dion, N. P.; Jones, M. A., 1998, Hydrology

Society of America Bulletin, v. 85, no. 5, p. 785-794.

rocks and minerals for major and trace elements on a single low dilution Li-tetraborate fused bead: Advances in X-ray Analysis, King, K. W.; Tarr, A. C.; Carver, D. L.; Williams, R. A.; Worley, D. M.,

and vicinity: Seismological Society of America Bulletin, v. 80, no. 5, p. 1057-1078. of Science thesis, 96 p., 3 plates.

Logan, R. L.; Polenz, Michael; Walsh, T. J.; Schasse, H. W., 2003a, Geologic map of the Squaxin Island 7.5-minute quadrangle, Mason and Thurston Counties, Washington: Washington Division of Geology and Earth Resources Open File Report 2003-23, 1 sheet, scale 1:24,000. Logan, R. L.; Walsh, T. J.; Polenz, Michael, 2003b, Geologic map of the Longbranch 7.5-minute quadrangle, Thurston, Pierce, and

Society of America Abstracts with Programs, v. 34, no. 5, p. A-109. Logan, R. L.; Walsh, T. J.; Schasse, H. W.; Polenz, Michael, 2003c, Geologic map of the Lacey 7.5-minute quadrangle, Thurston County, Washington: Washington Division of Geology and Earth Resources Open File Report 2003-9, 1 plate, scale 1:24,000.

Ludwig, K. R.; Muhs, D. R.; Simmons, K. R.; Halley, R. B.; Shinn, E. A., 1996, Sea-level records at ~80 ka from tectonically stable platforms—Florida and Bermuda: Geology, v. 24, no. 3, p. 211-214. Mix, A. C., 1987, The oxygen-isotope record of glaciation. *In* Ruddiman, W. F.; Wright, H. E., Jr., editors, North America and

geological research conducted by the

State of Washington, Department

surface geology: Earthquake Spectra, v. 8, no. 4, p. 501-527.

landscape development by the Puget lobe ice sheet. *In* Lasmanis, Washington State: Washington Division of Geology and Earth Resources Bulletin 80, p. 207-218.

Lowland, Washington, during ice-sheet glaciation: Geology, v. 22,

Borden, R. K.; Troost, K. G., 2001, Late Pleistocene stratigraphy in the Washington Division of Geology and Earth Resources Report of

County, Washington: Western Washington University Master of Science thesis, 175 p., 2 plates.

Garling, M. E.; Molenaar, Dee; and others, 1965, Water resources and

geology of the Kitsap Peninsula and certain adjacent islands: Washington Division of Water Resources Water-Supply Bulletin 18, Glassley, W. E., 1974, Geochemistry and tectonics of the Crescent

volcanic rocks, Olympic Peninsula, Washington: Geological Johnson, D. M.; Hooper, P. R.; Conrey, R. M., 1999, XRF analysis of

1990, Seismic ground-response studies in Olympia, Washington,

Lea, P. D., 1984, Pleistocene glaciation at the southern margin of the Puget lobe, western Washington: University of Washington Master

Mason Counties, Washington: Washington Division of Geology and Earth Resources Open File Report 2003-21, 1 sheet, scale 1:24,000. Logan, R. L.; Walsh, T. J.; Polenz, Michael; Schasse, H. W., 2002, Pleistocene tephrostratigraphy and paleogeography of the south Puget Sound basin near Olympia, WA [abstract]: Geological

adjacent oceans during the last glaciation: Geological Society of America DNAG Geology of North America, v. K-3, p. 111-125. Morrison, R. B., 1991, Introduction. *In* Morrison, R. B., editor,

Quaternary nonglacial geology—Conterminous U.S.: Geological Society of America DNAG Geology of North America, v. K-2, p. 1-Noble, J. B.; Wallace, E. F., 1966, Geology and ground-water resources

of Thurston County, Washington; Volume 2: Washington Division of Water Resources Water-Supply Bulletin 10, v. 2, 141 p., 5 plates. Palmer, S. P.; Walsh, T. J.; Gerstel, W. J., 1999a, Geologic folio of the Olympia-Lacey-Tumwater urban area, Washington-Liquefaction susceptibility map: Washington Division of Geology and Earth Resources Geologic Map GM-47, 1 sheet, scale 1:48,000, with

Palmer, S. P.; Walsh, T. J.; Gerstel, W. J., 1999b, Strong-motion amplification maps of the Tumwater and Lacey 1:24,000-scale quadrangles, Washington. In U.S. Geological Survey, National Earthquake Hazards Reduction Program, External Research Program, annual project summaries, Volume 40, Pacific Northwest: U.S. Geological Survey, 9 p.

Porter, S. C.; Swanson, T. W., 1998, Radiocarbon age constraints on rates of advance and retreat of the Puget lobe of the Cordilleran ice sheet during the last glaciation: Quaternary Research, v. 50, no. 3,

Pringle, R. F., 1990, Soil survey of Thurston County, Washington: U.S. Soil Conservation Service, 283 p., 49 plates. Rau, W. W., 1981, Pacific Northwest Tertiary benthic foraminiferal biostratigraphic framework—An overview. In Armentrout, J. M., editor, Pacific Northwest Cenozoic biostratigraphy: Geological

Society of America Special Paper 184, p. 67-84. Schasse, H. W.; Logan, R. L.; Polenz, Michael; Walsh, T. J., 2003, Geologic map of the Shelton 7.5-minute quadrangle, Mason and Thurston Counties, Washington: Washington Division of Geology and Earth Resources Open File Report 2003-24, 1 sheet, scale

Shannon & Wilson, Inc., 1999, Phase 2 geotechnical report, Sunrise Beach Road NW landslide, Thurston County Department of Roads and Transportation Services, Thurston County, Washington: Shannon & Wilson, Inc. [under contract to] Thurston County Department of Roads and Transportation Services, 1 v.

Tabor, R. W.; Cady, W. M., 1978, Geologic map of the Olympic Peninsula, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-994, 2 sheets, scale 1:125,000. Thorson, R. M., 1981, Isostatic effects of the last glaciation in the Puget

Lowland, Washington: U.S. Geological Survey Open-File Report 81-370, 100 p., 1 plate. Troost, K. G., 1999, The Olympia nonglacial interval in the southcentral Puget Lowland, Washington: University of Washington Master of Science thesis, 123 p.

Varnes, D. J., 1978, Slope movement types and processes. *In* Schuster, R. L.; Krizek, R. J., editors, Landslides—Analysis and control: National Research Council Transportation Research Board Special

Report 176, p. 11-33, 1 plate. Walsh, T. J., compiler, 1987, Geologic map of the south half of the Tacoma quadrangle, Washington: Washington Division of Geology

and Earth Resources Open File Report 87-3, 10 p., 1 plate, scale Walsh, T. J.; Korosec, M. A.; Phillips, W. M.; Logan, R. L.; Schasse, H. W., 1987, Geologic map of Washington—Southwest quadrant: Washington Division of Geology and Earth Resources Geologic Map GM-34, 2 sheets, scale 1:250,000, with 28 p. text.

Walsh, T. J.; Logan, R. L.; Polenz, Michael; Schasse, H. W., 2003a, Geologic map of the Nisqually 7.5-minute quadrangle, Thurston and Pierce Counties, Washington: Washington Division of Geology and Earth Resources Open File Report 2003-10, 1 sheet, scale

Walsh, T. J.; Polenz, Michael; Logan, R. L.; Lanphere, M. A.; Sisson,

T. W., 2003b, Pleistocene tephrostratigraphy and paleogeography of

southern Puget Sound near Olympia, Washington. In Swanson, T. W., editor, Western Cordillera and adjacent areas: Geological Society of America Field Guide 4, p. 225-236. Washington Department of Ecology, 1980, Coastal zone atlas of Washington; volume 8, Thurston County: Washington Department

of Ecology, 1 v., maps, scale 1:24,000. Washington Public Power Supply System, 1974, Analysis of accelerograms recorded at Olympia, Washington. In Washington Public Power Supply System, WPPSS nuclear project no. 3—Preliminary safety analysis report: Washington Public Power Supply System Docket no. 50-508, Preliminary Safety Analysis Report, Amendment 2, Appendix 2.5.K, p. 2.5.K-1 - 2.5.K-25, 13

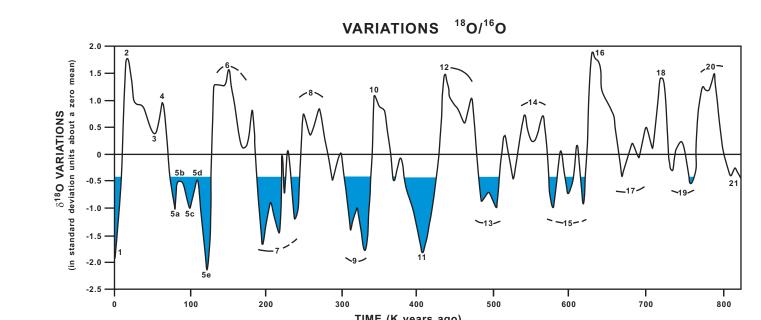


Figure 1. Marine oxygen-isotope stages (from Morrison, 1991). The numbers within the graph are stage numbers; the evennumbered peaks (at top) are glacial maxima and the odd-numbered troughs (at bottom) are interglacial minima. The blue areas indicate interglacial episodes, based on a cutoff at -0.5 δ<sup>18</sup>O oxygen-isotope values (equivalent to Holocene interglacial values).

> Table 1. Radiocarbon ages (by Beta Analytic, Inc.) reported in this study. \*, the location convention used herein consists of, in order, township (north), range (east or west), and section, followed by a period and then two digits indicating tenths of a mile east and north, respectively, from the southwest section corner. For example, 19-2W-33.85 indicates that the sample was taken from 0.8 mi east and 0.5 mi north of the southwest corner of section 33, township 19 north, range 2 west. In Donation Land Claim areas (odd-shaped sections), the letter 'X' is substituted for the distance from the southwest section corner (for example, 19-2W-41.X); additional digits are used as a unique sample identifier where multiple samples were collected from the same location. \*\*, radiocarbon ages given as conventional radiocarbon age in uncalibrated radiocarbon years before present, where 'present' is 1950 A.D.; reported uncertainty is one standard deviation, where applicable

Distriction This was done is suppoided							
Disclaimer: This product is provided 'as is' without warranty of any kind, either expressed or implied, including,	Map no.	Location	Location detail*	Map unit	Material	Sample no.	Conventional age (yr B.P.)**
but not limited to, the implied warranties of merchantability and fitness for a particular use. The Washington Department of Natural Resources will not be liable to the user of this product for any activity involving the product with respect to the following: (a) lost profits, lost savings, or any other consequential damages; (b) the fitness of the product for a particular purpose; or (c) use of the product or results obtained from use of the product. This product is considered to be exempt from the Geologist Licensing Act [RCW 18.220.190 (4)] because it is	1	Mission Creek drainage	18-2W-53.XX	Qps	wood	113497	>47,470?
	2	Budd Inlet at Gull Harbor	19-2W-41.X	Qps	wood	167214	>46,290
	3	Budd Inlet, Tugboat Annie's restaurant	18-2W-57.X	Qps	peaty silt	167210	>45,420
	4	Budd Inlet at Little Tykle Cove	19-2W-33.85	Qps	peaty silt	167213	>44,370
	5	Budd Inlet at Big Tykle Cove	19-2W-44.X	Qps	peat	167215	>44,760
	6	Natural Resources Building, Washington St., Olympia	18-2W-47.X4A	Qp	wood	39190	$10,710\pm100$
	6	Natural Resources Building, Washington St., Olympia	18-2W-47.X4B	Qp	wood	39191	540 ±50

Table 2. Geochemical analyses of Crescent Formation basalt performed by x-ray fluorescence at the Washington State University GeoAnalytical Lab. Instrumental precision is described in detail in Johnson and others (1999). Major elements are normalized on a volatile-free basis, with total Fe expressed as FeO. †, values greater than 120 percent of the laboratory's highest standard

MAJOR ELEMENTS—NORMALIZED (in weight percent)													
Loc.	Sample no.	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	TiO <sub>2</sub>	FeO	MnO	CaO	MgO	K <sub>2</sub> O	Na <sub>2</sub> O	P <sub>2</sub> O <sub>5</sub>	Original tota	
1	SCH1016011	49.36	14.69	2.621	11.70	0.195	12.23	6.00	0.33	2.59	0.281	98.57	
2	SCH1016012	49.07	14.79	2.296	12.15	0.201	11.85	6.47	0.38	2.53	0.251	98.29	
3	SCH1016013	48.75	15.56	1.947	11.60	0.195	13.09	6.04	0.22	2.40	0.190	98.39	
4	SCH1016014	48.35	15.49	1.911	11.91	0.191	11.23	7.17	0.21	3.34	0.186	97.20	
5	SCH1017011	48.78	14.18	2.872	12.76	0.197	12.17	6.00	0.17	2.56	0.298	98.27	

RACE ELEMENTS (in parts per million)																		
Loc.	Sample no.	Ni	Cr	Sc	$\mathbf{V}$	Ba	Rb	Sr	Zr	Y	Nb	Ga	Cu	Zn	Pb	La	Ce	Th
1	SCH1016011	84	234	36	368	76	2	245	165	36	16.5	22	†198	103	0	17	30	0
2	SCH1016012	62	142	40	337	86	5	254	153	30	15.2	1.8	152	96	3	18	21	4

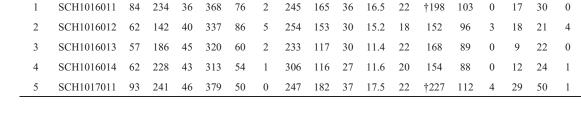
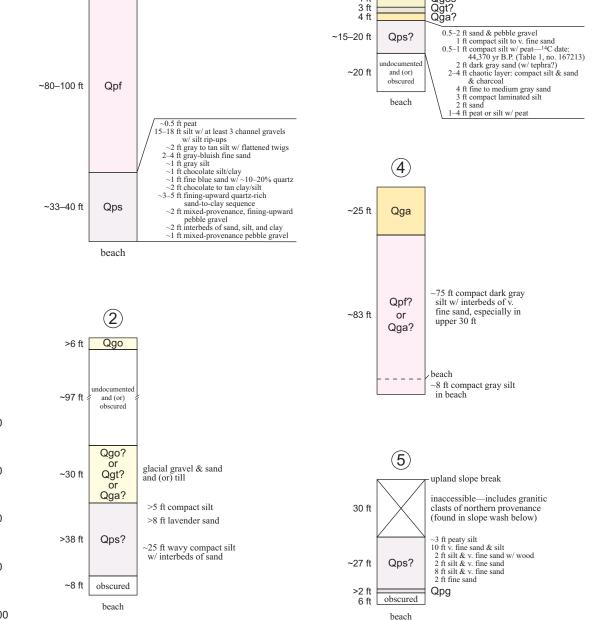




Figure 4. Outcrop of the Tumwater sand (unit Qgos) showing prominent northwarddipping foreset beds implying deposition by north-flowing streams into glacial Lake



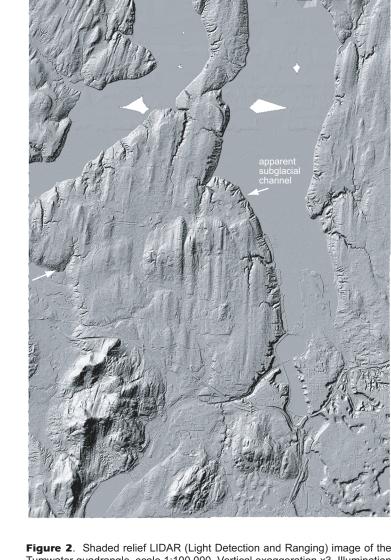


Figure 2. Shaded relief LIDAR (Light Detection and Ranging) image of the Tumwater quadrangle, scale 1:100,000. Vertical exaggeration x3. Illumination is from the northwest at an angle of 40 degrees. Note apparent subglacial channel trending approximately N60°E cutting drumlinized surface in the center of the quadrangle. This feature continues onto the Summit Lake quadrangle to the west where it coincides with Perry Creek

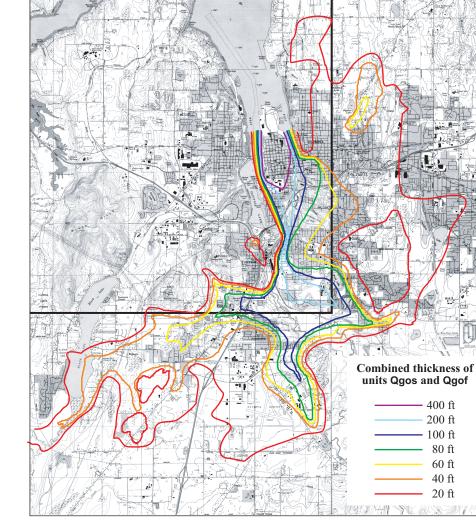


Figure 3. Combined thickness of units Qgos and Qgof from water wells located by Drost and others (1998) and geotechnical borings from Palmer and others (1999a); shown only where at least 20 ft thick. Note that these sediments were deposited in a channel to the west of the current channel and that the Deschutes River is superposed. The southern three-quarters of the Tumwater quadrangle is outlined in black